Emergent Time and Gravity from Irreversible Interaction Events

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Abstract

We develop an event-based extension of quantum theory in which irreversible interaction events are taken as physically primary, and apply this framework to the emergence of time and effective gravitational behavior. An event is defined as a non-invertible completely positive, trace-preserving (CPTP) map acting on quantum states. Unitary dynamics are treated as an effective interpolation between events rather than as fundamental evolution. Time is defined as a partial ordering induced by irreversible events, while continuous time arises as a coarse-grained limit at high event density. We introduce event density as an operational quantity governing both decoherence and temporal accumulation, and show that spatial gradients of event density naturally give rise to effective gravitational time-dilation phenomena. No new force laws, spacetime curvature, or quantum gravity dynamics are postulated. Instead, gravity and time are shown to emerge as scale-dependent descriptions arising from irreversible event structure. The formulation is compatible with standard quantum mechanics, open-system dynamics, and general relativity in their respective domains, while clarifying the physical role of irreversibility in linking quantum theory and spacetime descriptions.

1 Introduction

The tension between quantum theory and spacetime-based physics remains one of the central unresolved problems in fundamental physics. Quantum mechanics presupposes an external time parameter with respect to which unitary evolution is defined, while spacetime theories such as general relativity treat time as a geometric component of a dynamical manifold. Neither framework provides a satisfactory account of the physical origin of temporal ordering itself.

A common but often implicit assumption in both frameworks is the treatment of physical processes as fundamentally reversible, with irreversibility introduced only phenomenologically or through boundary conditions. In quantum mechanics, measurement is modeled as an exceptional, non-unitary intervention, while decoherence is often described as an effective loss of information rather than a physically primary process.

In two preceding works, we proposed a reformulation of quantum theory centered on irreversible interaction events. In the first paper, decoherence was modeled as arising from a

finite density of irreversible events, leading to experimentally testable consequences in gravitational environments. In the second paper, quantum measurement was reinterpreted as a special case of irreversible events represented by non-invertible CPTP maps. In both cases, irreversibility was treated as a physical property rather than an epistemic limitation.

The purpose of the present paper is to extend this event-based framework to the concepts of time and gravity. Rather than introducing new dynamical postulates, we reorganize existing structures by taking irreversible events as primitive. Time is defined as an ordering relation induced by such events, and gravity is interpreted as an effective phenomenon arising from spatial variations in event density.

This work does not aim to construct a full theory of quantum gravity. Instead, it seeks to identify a minimal and stable conceptual bridge between quantum foundations and spacetime descriptions, grounded in the physical reality of irreversible interactions.

2 Irreversible Interaction Events

2.1 Definition

We define an **irreversible interaction event** as a physical process represented mathematically by a completely positive, trace-preserving (CPTP) map

$$\mathcal{E} : \rho \mapsto \mathcal{E}(\rho),$$

acting on a density operator ρ, such that no completely positive inverse map $\mathcal{E}^{-1}$ exists. Non-invertibility is taken as the defining physical feature of an event.

This definition aligns with the standard formalism of open quantum systems, but differs in interpretation: irreversibility is not viewed as an approximation or environmental artifact, but as a physically primary property of interactions.

2.2 Unitary Evolution as Effective Description

Between events, quantum systems are assumed to undergo unitary evolution

$$\rho(t) = U(t)\,\rho(0)\,U^{\dagger}(t),$$

where the time parameter t is understood as an effective ordering variable rather than a fundamental entity. Unitary dynamics serve as an interpolation scheme between irreversible events, valid when event density is sufficiently low or when events can be coarse-grained.

3 Event-Ordered Time (Mathematical Formulation)

3.1 Event Set and Partial Order

Let $\mathcal{E} = \{E_i\}$ denote the set of irreversible interaction events. Each event is represented by a completely positive, trace-preserving (CPTP) map

$$E_i : \rho \mapsto \mathcal{E}_i(\rho), \qquad \nexists\, \mathcal{E}_i^{-1} \text{ that is completely positive.}$$

Irreversibility, expressed as non-invertibility, is taken as the defining physical property of an event.

Definition 1 (Event Order)**.** *Define a binary relation* $\prec \subset \mathcal{E} \times \mathcal{E}$ *by*

$$E_i \prec E_j \quad \Longleftrightarrow \quad \mathrm{Im}\big(\mathcal{E}_j \circ \mathcal{E}_i\big) \subsetneq \mathrm{Im}\big(\mathcal{E}_j\big),$$

i.e. the occurrence of E_i *strictly reduces the physically accessible state space prior to* E_j*.*

Proposition 1. *The relation* $\prec$ *defines a strict partial order on* $\mathcal{E}$*.*

Proof. Irreflexivity follows from non-invertibility. Transitivity follows from composition of CPTP maps. If both $E_i \prec E_j$ and $E_j \prec E_i$ held, the composition would admit an effective inverse, contradicting irreversibility. □

3.2 Emergent Time Functional

Let γ denote a worldline or interaction history, and let

$$N_E(\gamma) := \#\big\{E_i \in \mathcal{E} \;\big|\; E_i \text{ occurs along } \gamma\big\}.$$

Definition 2 (Emergent Time)**.** *Define the emergent time functional*

$$\tau(\gamma) := \alpha\, N_E(\gamma), \qquad \alpha > 0.$$

Lemma 1. *In the limit of high event density,* τ *converges to a continuous, monotonic parameter.*

Sketch of proof. Under coarse-graining, discrete event counts admit smooth limits by the law of large numbers. □

3.3 Arrow of Time

Theorem 1 (Arrow of Time)**.** *If all physical interactions are represented by non-invertible CPTP maps, then the induced ordering* $\prec$ *is globally time-oriented.*

Proof. Assume the existence of a closed cycle of events. The corresponding composition would define an effective inverse map, contradicting non-invertibility. □

4 Event Density and Effective Gravity (Mathematical Formulation)

4.1 Event Density

Introduce an ordering parameter λ along a worldline γ.

Definition 3 (Event Density)**.**

$$\rho_E(\lambda) := \frac{dN_E}{d\lambda}.$$

The accumulated event-ordered time is then given by

$$\tau(\gamma) = \int_{\gamma} \rho_E(\lambda)\, d\lambda.$$

This expression defines clocks operationally as **event counters**.

4.2 Differential Aging

Consider two worldlines γ_1 and γ_2 traversing regions with distinct event densities. The relative accumulation of time satisfies

$$\Delta\tau = \int_{\gamma_1} \rho_E\, d\lambda - \int_{\gamma_2} \rho_E\, d\lambda.$$

Proposition 2. *Spatial gradients of ρ_E induce systematic differential aging between clocks.*

4.3 Effective Gravitational Interpretation

Under suitable coarse-graining, one may identify

$$\rho_E(x) \;\propto\; \sqrt{-g_{00}(x)},$$

recovering the standard gravitational redshift relation as an effective description, without introducing fundamental spacetime curvature or force laws.

5 Relation to Existing Frameworks

5.1 General Relativity

General relativity provides a geometric description of gravity in terms of spacetime curvature. The present framework does not dispute its empirical success, but reinterprets geometric structures as effective descriptions arising from coarse-grained event statistics.

Gravitational time dilation is recovered operationally through differential accumulation of event-ordered time, without postulating curvature at the fundamental level.

5.2 Causal Set Theory

Causal set approaches model spacetime as a discrete partially ordered set. While sharing an emphasis on ordering, the present framework differs by grounding the order in physically defined irreversible events rather than abstract elements.

Event density is defined operationally through interaction statistics, rather than through the cardinality of set elements.

6 Implications

The framework unifies decoherence, measurement, time, and gravity under a single physical concept: irreversible interaction events. Decoherence rates, clock behavior, and effective gravitational phenomena are governed by the same underlying event statistics.

This suggests experimental access through precision timekeeping, gravitational decoherence tests, and controlled open-system dynamics, without requiring Planck-scale physics.

7 Conclusion

By taking irreversible interaction events as physically primary, we have shown that time and gravity can be understood as emergent, scale-dependent descriptions rather than fundamental structures. Time arises as an ordering relation induced by non-invertible events, while gravity emerges from spatial variations in event density.

The present work provides a minimal and conceptually stable bridge between quantum foundations and spacetime physics, without introducing new dynamics or speculative assumptions. Open questions remain concerning the microscopic origin of event irreversibility and its precise quantitative relation to spacetime geometry.

References

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